The RIDGE pipeline as a method to search for gravitational waves associated with magnetar bursts

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ABSTRACT

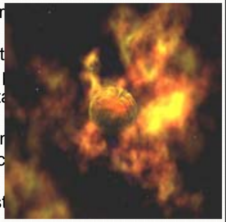
RIDGE is a data analysis pipeline which implements a regularized, coherent approach to search for short-duration gravitational wave (GW) signals in the data from a network of gravitational wave detectors. We discuss the RIDGE pipeline and describe its potential in the search for gravitational waves associated with soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs). SGRs and AXPs are thought to be the result of seismic events in the crust of a magnetar (a neutron star with a strong magnetic field approximately 10^{14} Gauss) which could produce short bursts of gravitational waves. [6]

METHODOLOGY

This project is an assessment of RIDGE in its ability to help detect potential GW signals. Upon receiving data from a network, RIDGE analyzes manually selected data sections specified by input parameters (which must be carefully chosen). For example, parameters such as data length and frequency range must be selected that will provide RIDGE with an appropriate data set to filter potential GW detections from stationary and transient noise. The purpose of RIDGE is to reduce the chance of generating false alarms and at the same time, increase the signal-to-noise ratio by combining the data streams coherently.

MAGNETARS

There are many different types of astronomical GW sour[...] that theoretically can be detected: but this research project involves the specific category of soft γ-ray repeat[...] and anomalous X-ray pulsars, which are produced by a [...]ticular type of celestial body called a *magnetar*. Magneta[...] are neutron stars with tremendously powerful magnetic fields. The magnetic field within it is not static, but dynar[...] which retards the star's spin frequency and induces crac[...] (seismic events) along the crust that in turn, release extraordinary amounts of electromagnetic radiation burst[...] usually in the frequency range of X-rays and γ-rays and in addition, may produce short bursts of GWs. [6,7]

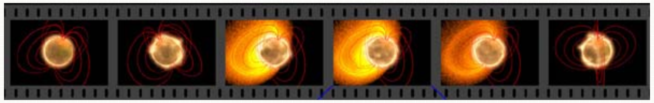


http://science.nasa.gov/newhome/headlines/mag_pix/still-1-final.jpg

(Recently, an observation of a magnetar-like emission from a young pulsar shows that the magnetic and rotational thresholds to produce this sort of emission can be lowered through unique behavior of flux and timing. [5])

This research project will simulate data based upon the magnetar SGR 1806-20 to examine the applicability of RIDGE.

SEQUENCE OF A MAGNETAR BURST [6]:



http://solomon.as.utexas.edu/~duncan/magnetar.html

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[3] Mohanty, S.D. "RIDGE: Status and Analysis Plan" (presentation)
[4] M Rakhmanov "Rank deficiency and Tikhonov regularization in the inverse problem for gravitational
wave bursts" (2006)
[5] F. P. Gavriil, M. E. Gonzalez, E. V. Gotthelf, V. M. Caspi, M. A. Livingstone, P. M. Woods "Magnetar-like
Emission from the Young Pulsar in Kes 75"
[6] http://solomon.as.utexas.edu/~duncan/magnetar.html

RIDGE PIPELINE

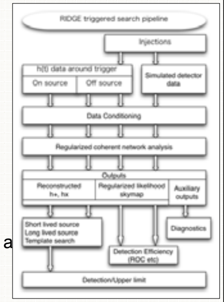
When a GW passes through the detector, the output is formatted as a linear combination of the incident GW and additive detector noise. [2] The data produced by the detectors is related to the GW signal by:

$$\begin{bmatrix} x_1(t) \\ \vdots \\ x_d(t) \end{bmatrix} = \begin{bmatrix} F_{1+}(\theta,\phi) & F_{1\times}(\theta,\phi) \\ \vdots & \vdots \\ F_{d+}(\theta,\phi) & F_{d\times}(\theta,\phi) \end{bmatrix} \begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ \vdots \\ n_d(t) \end{bmatrix}$$

data = detector response x gravitational wave + noise

$$X = A \times h + n$$

X : data given by multiple detectors
A : calculated by (1) the angle of location of supposed SGR a[...]
(2) the frequency of GW
h : supposed signal of GW
n : noises estimated by data conditioning



http://phys.utb.edu/~kazu/RIDGE/flowchart/index.html

The RIDGE pipeline is a coherent ***network analysis pipeline*** meaning that it combines the data from a network of detectors and searches for a common signal. It is implemented in MATLAB and uses the method of maximum likelihood with Tikhonov regularization. [3]

What is maximum likelihood of a GW signal?
Basically it uses the method of least squares to find the h that minimizes the following equation:

$$L(h) = || X - A*h ||^2$$

However, simply ensuring a signal that agrees with the data also causes fitting to the noise., thus Tikhonov regularization is employed. An extra term is added which penalizes overfitting:

$$L(h) = || X - A*h ||^2 + h^T*\Omega*h$$

where Ω is a Lagrange parameter which is chosen to balance between being true to the data and avoiding fitting the noise. [4]

RIDGE calculates the likelihood over a grid of sky locations, using the detector response A appropriate for each location. The set of values of likelihood at these sky locations is called a *sky-map*. A sky-map calculated for simulated LIGO data with no signal present and a sky-map that includes a simulated signal will show a significant difference in their patterns. Two different statistics are calculated based on the changes in the sky-map: (1) R_{rad} : the difference between the baseline map and each time segment map and (2) R_{mm} : the correlation between the baseline map and each time segment map:

$$R_{mm} = \frac{\Sigma[(S_{max} - \bar{S}_{max})(S_0 - \bar{S}_0)]}{norm(S_{max} - \bar{S}_{max}) * norm(S_0 - \bar{S}_0)}$$

(1)

$$R_{rad} = \left[\left(\frac{\max_{\theta,\varphi} S(\theta,\varphi)}{\max_{\theta,\varphi} \bar{S}_0(\theta,\varphi)} - 1 \right)^2 + \left(R_{mm} \frac{\max_{\theta,\varphi} \bar{S}_0(\theta,\varphi)}{\max_{\theta,\varphi} \bar{S}_0(\theta,\varphi)} - 1 \right)^2 \right]^{1/2}$$

(2)

where $S_{max} = \max_{\theta,\varphi} S(\theta,\varphi)$ and $S_0 = \max_{\theta,\varphi} \bar{S}_0(\theta,\varphi)$;

$\bar{S}_0$ S(θ,φ) is the maximum likelihood value at each sky position;
[max/min]S(θ,φ) represents [max/min] value of S(θ,φ); and
(θ,φ) is the collection average of the points of sky-maps that do not have any GW

RESULTS

2000 seconds of simulated signals with central frequencies equal to oscillation frequencies observed in X-rays produced by SGR 1806-20 (the burst that occurred on Dec 1, 2005 at 09:58:40 UTC), were analyzed with a simulated noise baseline (similar to that of LIGO) to assess the applicability of the RIDGE pipeline in searching for GWs from magnetars. The added signals were circularly polarized sine gaussians with three different central frequencies: 92.9 Hz, 625.5 Hz, and 1837 Hz. that were added with a magnitude scaled such that the h_{RSS} was 10^{-21}. The lower frequency 92.9 Hz lies within the most sensitive range of LIGO (simulated signal at 92.9 Hz with 10x the h_{RSS} was processed to provide more visually contrasting outputs). The h_{RSS} is *strain root sum of squares* and is defined as: $\Sigma(h_{+i} + h_{\times i})^{1/2} / f_s$, where h_{+i} is the plus polarization; $h_{\times i}$ is the cross polarization of each element i; and f_s is the sampling frequency. [2]

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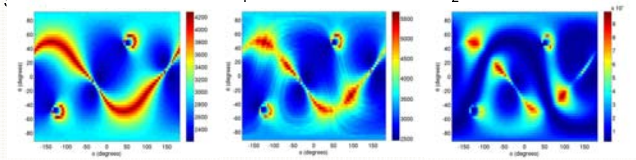
Sky maps: 1 2



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Potential signal present: (1) at 92.9 Hz, ($h_{RSS} = 10^{-21}$)
(2) at 92.9 Hz ($h_{RSS} = 10^{-20}$)

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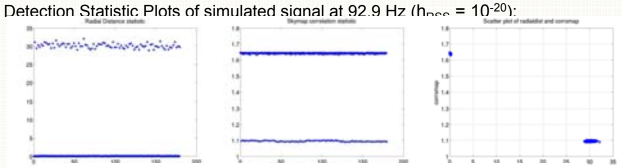
Detection Statistic Plots of simulated signal at 92.9 Hz ($h_{RSS} = 10^{-20}$):



R_{rad} R_{mm} Plot of: R_{mm} vs. R_{rad}

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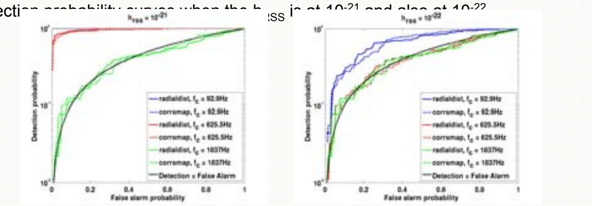
Detection probability curves when the h_{RSS} is at 10^{-21} and also at 10^{-22}



$h_{RSS} = 10^{-21}$ $h_{RSS} = 10^{-22}$

CONCLUSION

Based on the detection probability curves, it is shown that the two statistics that RIDGE uses (R_{rad} and R_{mm}) are *effective* in differentiating potential GW signals from the noise. When the h_{RSS} is at 10^{-21}(which is the highest value we can likely expect from a GW), RIDGE is 100% successful in this differentiation at the lower frequency, nearly so for the middle frequency, and to a lesser degree for the higher frequency. Even when the h_{RSS} is 10 times weaker (equal to 10^{-22}), RIDGE can distinguish a signal near 100 Hz. [1]